BIOFUELS

Biomass Yield, Phenology, and Survival of Diverse Switchgrass Cultivars and Experimental Strains in Western North Dakota

J. D. Berdahl,* A. B. Frank, J. M. Krupinsky, P. M. Carr, J. D. Hanson, and H. A. Johnson

ABSTRACT

Switchgrass (*Panicum virgatum* L.) has been identified as a potential biofuel crop for the northern Great Plains region of the USA. Biomass yield and survival percentage in western North Dakota were measured for 3 yr at three field sites, and plant development was monitored for 2 yr at one site to determine adaptation and stability of performance for eight diverse switchgrass cultivars and experimental strains. Harvest treatments were single annual cuttings in mid-August or mid-September. Except for 'Dacotah', ND3743, and 'Sunburst', all other entries originated greater than 500 km south of the evaluation sites and were subject to winter injury. Sunburst, from southern South Dakota, ranked first or second in biomass yield in all environments and was the top-yielding entry in all environments in the third production year, a drought year at all sites. 'Trailblazer' ranked first, second, or third in biomass yield in all environments while yield ranking of the other entries was not consistent. Genotype × environment interactions occurred for biomass yield and would be expected based on the wide range in origin among the eight populations. Survival percentage was equal for the two harvest dates, but all eight populations averaged greater biomass yields at the mid-September (5.98 Mg ha^{-1}) than the mid-August (5.51 Mg ha^{-1}) harvest. Biomass yield of Sunburst at the site with the greatest yield potential ranged from 3.20 Mg ha^{-1} in a drought year to 12.48 Mg ha^{-1} in a year with above-average precipitation. Biomass yield of adapted switchgrass cultivars fluctuated widely in western North Dakota, depending in large part on available soil water.

Switchgrass is a perennial warm-season grass that is native to the tallgrass prairie of North America (Moser and Vogel, 1995). Native switchgrass germplasm is distributed over a wide geographic area, and improved cultivars with high biomass potential have been developed (Hopkins et al., 1995a, 1995b). The U.S. Department of Energy, in cooperation with several state universities and the USDA, has identified switchgrass as having good potential as a biofuel crop (Vogel, 1996). Economic analyses (McLaughlin et al., 2002) indicate that switchgrass used as a biofuel crop would be economically competitive with other crop species in much of the northern Great Plains region of the USA, including cropland areas in central and western North Dakota. These economic analyses assumed a minimum biomass yield of 9.0 Mg ha^{-1}, and sustained yields this great on dryland sites have not been documented in the study area.

The transition zone in the northern Great Plains between native tallgrass prairie on the east and midgrass prairie on the west occurs at approximately 98° W longitude (Moore and Lorenz, 1985). West of 98° W longitude, switchgrass occurs naturally on mesic sites such as river valleys and other low-lying areas. Water use efficiency of switchgrass evaluated in humid environments is approximately 50% greater than that of cool-season grass species (Stout et al., 1988), but yield potential and water use efficiency of current switchgrass cultivars in subhumid to semiarid northern environments, where soil water is often limiting, is not known.

Switchgrass cultivars of southern origin such as Cave-In-Rock (southern Illinois) and Blackwell (north-central Oklahoma) had no appreciable winter injury over a 4-yr period in a previous study (Jacobson et al., 1986) with test sites near Fergus Falls (west-central Minnesota), Upham (north-central North Dakota), Pierre (central South Dakota), and Lake Andes (south-central South Dakota). Madakadze et al. (1998) evaluated nine genetically diverse switchgrass populations in southwest Quebec (45°28′ N lat) and reported that late-maturing populations that maintained high leaf area index values late into the growing season had the greatest potential biomass yield from a single annual harvest. Winter injury was not reported in the Quebec study over a 4-yr period. Vogel et al. (1985) concluded that improvements in biomass yield of switchgrass cultivars had largely resulted from selecting genotypes originating at lower latitudes and moving them north where they would flower later due to photoperiod response to longer daylength.

Significant cultivar × environment interactions for biomass yield of switchgrass have been reported in several studies (Hopkins et al., 1995a; Madakadze et al., 1998; Sanderson et al., 1999; Casler and Boe, 2003). Environments in western North Dakota are limited in length of growing season, often limited by low precipitation, and subject to severe winter stress. These environments impose high levels of winter and drought stress and are unique from those of other study sites reported in the literature.

Objectives of this study were to ascertain biomass yield, phenology, and survival of eight diverse switchgrass cultivars and experimental strains harvested annually in

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Abbreviations: DOY, day of year; R0, boot stage of reproductive-floral development; R3, inflorescence emerged/peduncle fully elongated; R5, postanthesis stage of reproductive-floral development; S2, soft-dough stage of seed development.

Table 1. Growing season precipitation during 2000 to 2002 at Mandan, ND, and 2001 to 2003 at Dickinson, ND.

	Mandan				Dickinson			
Month	2000	2001	2002	30-yr avg.	2001	2002	2003	30-yr avg.
	mm							
Apr.	33	50	29	39	52	41	11	39
May	67	46	8	62	40	38	64	57
June	111	117	30	77	160	123	62	90
July	65	193	54	78	91	73	21	60
Aug.	26	0	57	51	1	62	29	43
Sept.	30	29	10	41	57	3	73	41
Seasonal total	332	435	188	348	401	340	260	330

mid-August or mid-September to determine the feasibility of using switchgrass as a biofuel crop in western North Dakota.

MATERIALS AND METHODS

Switchgrass performance tests were established at two sites located approximately 5 km apart at the Northern Great Plains Research Laboratory, Mandan, ND (46°48′ N, 100°55′ W), and one site at the Dickinson Research Extension Center, Dickinson, ND (46°53′ N, 102°48′ W). Mandan Site 1 is drought prone due to sandy soil, Mandan Site 2 has relatively high potential for biomass yield, and Dickinson provides another environment with relatively high production potential located 165 km west of the Mandan sites. Soil at Mandan Site 1 was a Parshall fine sandy loam (coarse-loamy, mixed, superactive, frigid Pachic Haplustolls), and soil at Mandan Site 2 was a Wilton silt loam (fine-silty, mixed, superactive, frigid Pachic Haplustolls). Soil at the Dickinson site was a Farnuf fine sandy loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls). The growing season averages 125 frost-free days at Mandan and 112 d at Dickinson, with the first killing frost (<-2°C) in the fall occurring approximately 20 September (High Plains Regional Climate Center, 2004). Precipitation was recorded during the growing season at Mandan and Dickinson for the duration of the study (Table 1).

Eight switchgrass cultivars and experimental strains, all upland cytotypes (Hultquist et al., 1996; C.M. Taliaferro, unpublished data, 1999), were included in this study: Dacotah, ND3743, Summer, Sunburst, Trailblazer, Shawnee, OK NU-2, and Cave-In-Rock (Table 2). Except for Dacotah, ND3743, and Sunburst, all of the switchgrass populations that were evaluated originated south of 43° N latitude, which is greater than 500 km south of the evaluation sites in this study. Entries with origin south of 43° N latitude will hereafter be referred to as having southern origin. Moser and Vogel (1995) concluded that warm-season grass species generally should not be moved more than 500 km north of their area of origin because of potential stand losses from winter injury. Plant development of switchgrass responds to photoperiod, and southern types moved too far north continue vegetative growth during autumn, resulting in inadequate winter hardening.

The experimental design at all sites was a four-replicate randomized complete block with a split-plot arrangement of treatments. Whole plots consisted of a single mid-August or mid-September annual harvest, and cultivars and experimental strains were subplots, hereafter referred to as plots. Each plot consisted of five rows 6.1 m long with a 35-cm spacing between rows at the two Mandan sites and a 46-cm row spacing at Dickinson. The relatively wide row spacings are a recommended practice in semiarid regions (Jefferson and Kielly, 1998). Seeding rate was 130 pure live seeds per lineal meter of row (approximately 6.0 to 7.0 kg pure live seeds ha^{-1}). To reduce border effects, 0.5 m from the ends of each plot was cut to a 15-cm height before harvest. Biomass yield was measured by harvesting the remaining 5.1 m from the three center rows of each plot to a 15-cm height. Dry matter percentage of biomass from each plot was measured from a 0.4- to 0.8-kg grab sample that was dried at 60°C and used to adjust plot yields to a dry matter basis. Haun score (Haun, 1973), measured weekly, and heading date (50% of the panicles emerged 50% from the boot) were recorded at Mandan Site 2 in 2000 and 2001. Survival percentage of each plot was measured immediately after each harvest by counting the presence or absence of plants within rows from fifty 15- by 15-cm grid cells in accordance with a procedure modified from Vogel and Masters (2001). Survival percentage also was measured at the two Mandan sites in June 2003 before these study sites were terminated.

Seeding dates were 27 May 1999 at Mandan and 31 May 2000 at Dickinson. Five border rows of Dacotah switchgrass were sown adjacent to plots on the outside edge of the study

Table 2. Description and origin of cultivars and experimental strains tested at two North Dakota locations.

Entry	Description	Reference
Dacotah	bulk of 10 selected plants from open-pollination progeny of a collection made near Breien, ND (46°30′ N lat)	Barker et al., 1990
ND 3743	experimental strain derived from early maturing plants in a population Nebraska 28 (possibly a seed admixture) grown near Upham, ND (49° N lat)	D.A. Tober, personal communication
Summer	bulked seed of a polycross derived from a collection made near Nebraska City, NE (40°40′ N lat)	Alderson and Sharp, 1994
Sunburst	bulked seed from half-sib families of 10 selected plants obtained from a collection made in Union County, SD (43° to 42°40′ N lat)	Boe and Ross, 1998
Trailblazer	twenty-five clone synthetic selected for high digestibility from two experimental populations that were derived from collections made in Nebraska and Kansas (43° to 37° N lat)	Vogel et al., 1991
Shawnee	bulked seed of 78 polycross progenies selected for biomass yield and digestibility from the cultivar Cave-In-Rock	Vogel et al., 1996
OK NU-2	narrow-base experimental synthetic population from the Oklahoma Agric. Exp. Stn. (approximately 35° N lat)	C.M. Taliaferro, personal communication
Cave-In-Rock	seed increase of an accession collected near Cave-In-Rock, IL (38°28′ N lat)	Alderson and Sharp, 1994

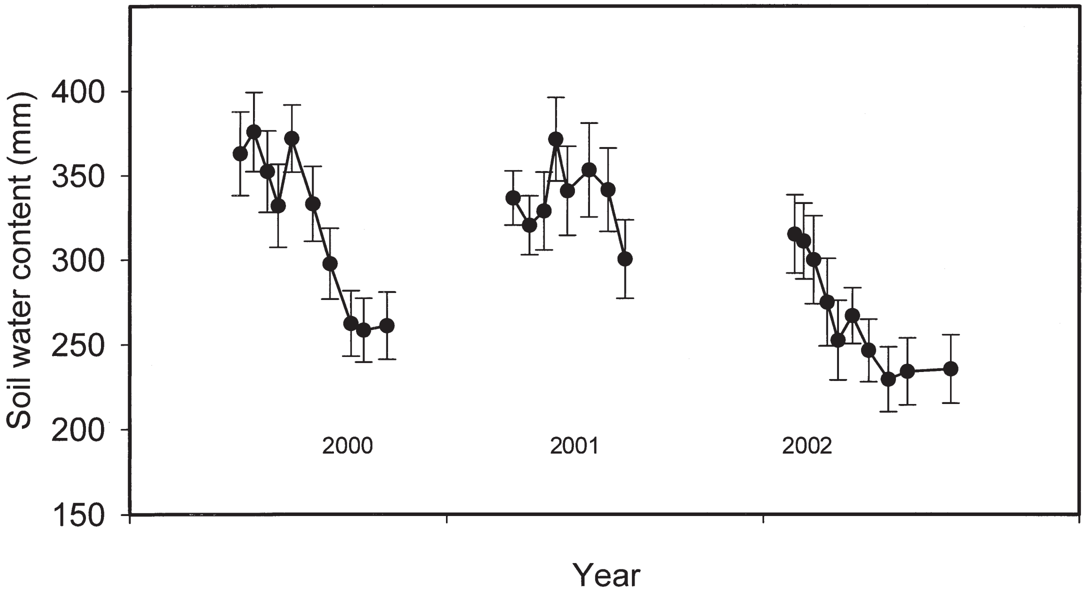

Fig. 1. Soil water content to a 1.2-m depth over the growing season (April through September) for plots of Sunburst and Dacotah switchgrass at two field sites near Mandan, ND. Vertical bars are standard errors of the mean of two cultivars, two sites, and four replicates (n = 16).

area at each field location to eliminate border effects caused primarily by unequal amounts of soil water. Alleyways in the study area were sown to meadow bromegrass (*Bromus riparius* Rehm.). The area seeded to switchgrass at each site was treated with 2.25 kg a.i. ha^{-1} atrazine (2-chloro-4-ethylamino-6-isopropylamino-*s*-triazine) immediately after seeding for weed control. At Dickinson, banvel (dimethylamine salt of 3,6-dichloro-*O*-anisic acid) at 0.55 kg a.i. ha^{-1} in June 2001 and 2,4-D amine (dimethylamine salt of 2,4-dichlorophenoxyacetic acid) at 0.55 kg a.i. ha^{-1} in May 2002 were applied for control of broadleaf weeds. Plots were cut at a 15-cm height in October of the establishment year, and forage was removed. Fertilizer was broadcast at 67 kg N ha^{-1} and 56 kg P ha^{-1} rates at Mandan and 56 kg N ha^{-1} and 56 kg P ha^{-1} at Dickinson in October of the establishment year. Thereafter, plots were fertilized with 67 kg N ha^{-1} at Mandan and 56 kg N ha^{-1} at Dickinson in October of each year. The N source was ammonium nitrate (34–0–0). Phosphorus was applied as ammoniated phosphate (11–48–0) at Mandan and triple superphosphate (0–44–0) at Dickinson.

Sunburst and Dacotah were each represented by an additional plot in each replicate at the two Mandan sites. Access tubes were placed in the center of these plots, and soil water content was measured at 0.3-m intervals to a 1.2-m depth using a neutron moisture meter. Measurements were made at approximately 2-wk intervals during the growing season. Total soil water content to a 1.2-m depth at each measurement date was averaged over the Sunburst and Dacotah plots and summarized for each year (Fig. 1).

A split-plot in space (locations) and time (years) was used in a combined analysis with harvest dates (whole plots), entries (subplots), locations, and years all considered fixed in the model. Replicates were nested within locations and considered as random effects along with all split-plot error terms. A SAS PROC MIXED analysis (Littell et al., 1996) was used where differences among harvest dates, entries, locations, and years and their interactions were tested by appropriate F ratios. Main effects and their interactions in this study were considered significant when $P \leq 0.05$. Differences among entries and harvests within each location and year were compared using a protected LSD test at $P \leq 0.05$ from separate analyses for individual locations and years.

RESULTS AND DISCUSSION

All eight entries averaged greater biomass yields at the mid-September than the mid-August harvest (Table 3), but some entries had a greater relative increase than others. The two entries of North Dakota origin, Dacotah and ND3743, were at the S2 (soft dough) stage of development (Moore et al., 1991) at the mid-August harvest and had relatively small increases in biomass for the remainder of the growing season. In some instances, biomass yield of Dacotah and ND3743 had a negative response to the later harvest date. Shawnee and Cave-In-Rock also had relatively small increases in biomass past mid-August even though both entries were still in the boot stage (R0) at the early harvest date. Vogel et al. (2002) found that optimum biomass yields from switchgrass in the central Great Plains were obtained when plants were harvested at plant development stages R3 to R5 (panicle fully emerged from boot to postanthesis).

The short stature and early maturity of Dacotah and

Table 3. Mean biomass yields and survival percentages of eight switchgrass cultivars and experimental strains at two harvest dates pooled over three locations and 3 yr and heading date at one location pooled over 2 yr.

Entry	Biomass yield		Survival percentage		Heading date
	Aug.	Sept.	Aug.	Sept.	
	—— Mg ha^{-1} ——		—— % ——		DOY†
Dacotah	5.33	5.43	91	92	186
ND 3743	4.85	5.01	89	91	186
Summer	5.18	5.78	61	65	206
Sunburst	7.08	7.76	96	96	213
Trailblazer	6.50	7.35	93	93	227
Shawnee	5.50	5.76	87	82	230
OK NU-2	4.83	5.80	75	79	252
Cave-In-Rock	4.84	4.97	79	78	232
Mean	5.51	5.98	84	84	217
$LSD_{0.05}$	0.51	0.54	3	3	4

† DOY, day of year.

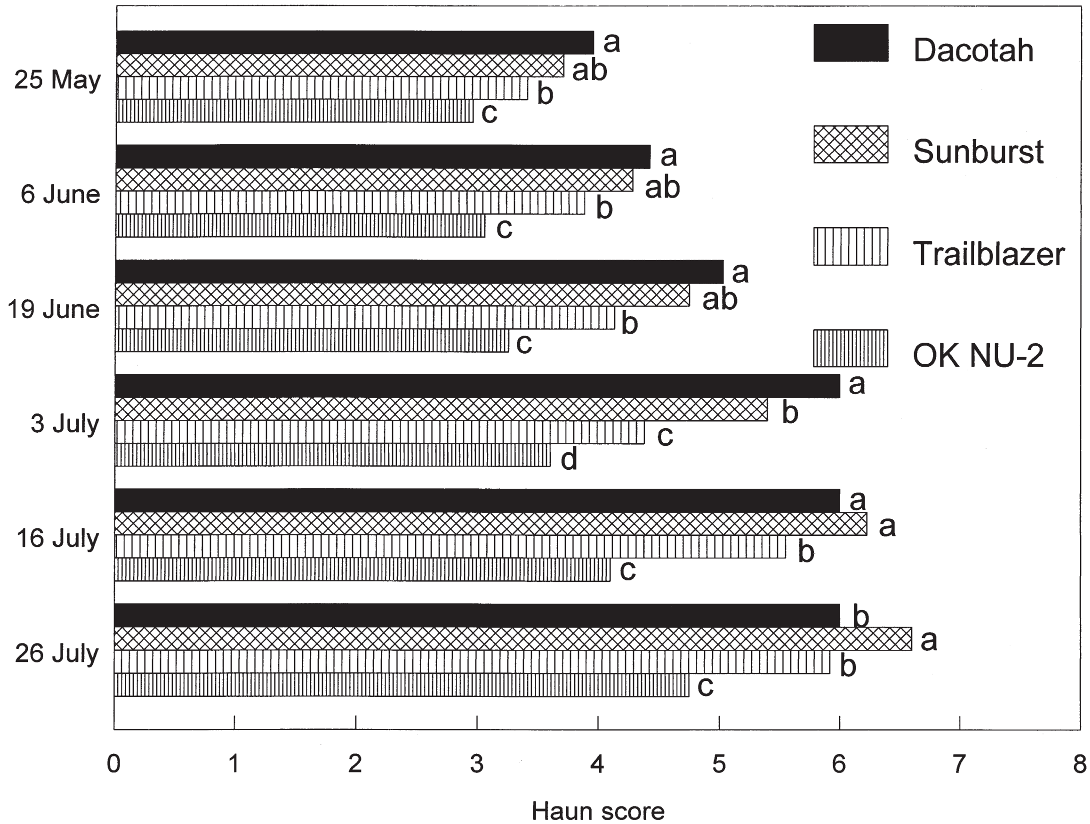

Fig. 2. Haun scores (Haun, 1973) of four switchgrass populations at Mandan, ND, Site 2 pooled over 2 yr. Within each date, Haun scores not followed by the same letter are significantly different at $P \leq 0.05$.

ND3743, entries of North Dakota origin (Table 2), resulted in a reduced number of phytomers (node + internode + leaf) (Fig. 2), which in turn reduced biomass yield (Table 3). These two entries had an average heading date of 5 July [DOY (day of year) 186] (Table 3) and produced a total of six phytomers. Sunburst, from South Dakota, had an average heading date of 1 August (DOY 213) and produced seven phytomers. Rate of phytomer development was similar for Dacotah, ND3743, and Sunburst. Later-maturing entries such as Trailblazer (average heading date 15 August, DOY 227) and OK NU-2 (average heading date 9 September, DOY 252) began phytomer development later in the spring and did not produce a maximum of seven phytomers until mid-August and early September, respectively. Average heading date of OK NU-2 occurred close to the average date of a first killing frost (20 September, DOY 263) at Mandan and Dickinson, which suggests that this entry would not obtain its maximum biomass yield potential in most years.

Harvest date had no appreciable effect on survival of the switchgrass populations included in this study over a 3-yr period (Table 3). However, Casler and Boe (2003) found that harvesting at a preanthesis stage of plant development reduced the ground area occupied by crown tissue in switchgrass swards at northern latitudes (43° to 44° N lat). They suggested that this reduction in crown tissue was due in large part to depletion of carbohydrate reserves resulting from forage regrowth after an early harvest. Little regrowth was evident after harvest in the North Dakota environments due to low levels of soil water after the mid-August harvest (Fig. 1) and relatively low temperatures after the mid-September harvest. Moser and Vogel (1995) reported that stand loss can occur in switchgrass if there are fewer than 6 wk between the last harvest and the first killing frost. In Texas, Sanderson et al. (1999) found that plots harvested late in the growing season had lower yields the following spring. Under conditions of the present North Dakota study, relatively severe winter and drought stress at a particular field site and year, rather than harvest date, appeared to be the most important factor influencing survival of individual entries. The three entries of northern origin, Dacotah, ND3743, and Sunburst, usually had the highest postwinter survival while the southern-most entries, Shawnee, OK NU-2, and Cave-In-Rock, generally had the greatest decrease in survival percentage from one year to the next (Fig. 3). Trailblazer and Summer, with origins in Nebraska, had greater declines in survival percentage than the three northern entries in some, but not in all, years or at all test sites.

The relative biomass yields of the eight cultivars and experimental strains were not consistent across different test sites in different years (Table 4). Changes in relative biomass yield among entries from 2000 to 2001 at the two Mandan sites were associated with survival. In February 2001, minimum air temperatures at Mandan were below −20°C for 16 consecutive days with essentially no snow cover (High Plains Regional Climate Center, 2004). Winter injury was common in field nurseries in

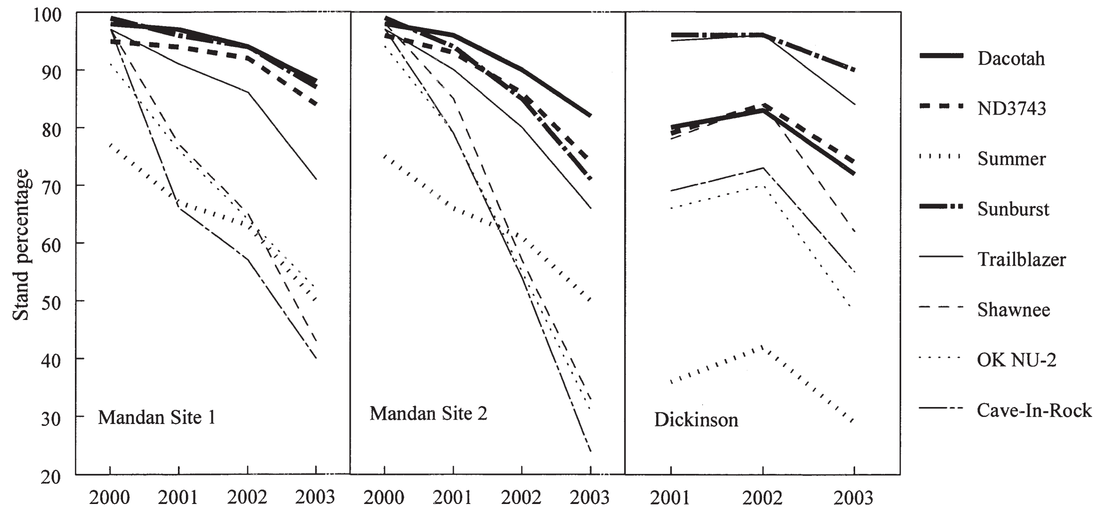

Fig. 3. Survival percentages of eight switchgrass cultivars and experimental strains measured at two North Dakota sites for 4 yr and at one site for 3 yr. Standard errors of an entry mean for 2000, 2001, 2002, and 2003, respectively, were 1.3, 2.9, 2.2, and 1.9 for Mandan Site 1 and 1.8, 2.3, 2.6, and 2.1 for Mandan Site 2. At Dickinson, standard errors of an entry mean for 2001, 2002, and 2003, respectively, were 3.8, 3.6, and 3.9.

the spring of 2001 at Mandan for several different grass and legume species (Meyer et al., 2002). Biomass decreased from 2000 to 2001 at Mandan sites for Shawnee, OK NU-2, and Cave-In-Rock, the three populations of southern-most origin (Table 2) and the latest heading dates (Table 3). These three entries also had the greatest decline in survival percentage from 2000 to 2001 at the Mandan sites (Fig. 3). Survival percentage continued to decline sharply for these entries in subsequent years at Mandan. Survival percentage measured at Mandan just before terminating tests at Site 1 and Site 2 in June 2003 was reduced for all entries compared with 2002, with Shawnee, OK NU-2, and Cave-In-Rock showing a rapid decline at Mandan Site 2. These results were not in agreement with those of Jacobson et al. (1986), who reported no winter injury to switchgrass cultivars, including Cave-In-Rock from southern Illinois and Blackwell from north-central Oklahoma, that were tested in North Dakota, South Dakota, and Minnesota for 4 yr. Results from the present North Dakota study suggested that switchgrass populations of southern origin that did not head until after mid-August in North Dakota environments did not acquire adequate dormancy before winter and were susceptible to injury and death from winter and other stresses. Trailblazer had apparent winter injury in the spring of 2001 at the Mandan sites, as evidenced by slow green-up and growth in early June, but survival percentage of Trailblazer did not decline as sharply as Shawnee, OK NU-2, and Cave-In-Rock. Biomass yield of Trailblazer had an apparent modest increase in 2001 compared with 2000 at Mandan (Table 4). The three populations of northern origin, Dacotah, ND3743, and Sunburst, had relatively stable survival percentages from 2000 to 2001 at Mandan and trended sharply upward in biomass yield from 2000 to 2001 (Table 4). Abnormally high rainfall occurred in June and July of 2001 (Table 1).

Dickinson had lower initial stand percentages than the Mandan sites (Fig. 3) because the soil surface became dry and crusted after seeding. Sunburst and Trailblazer had greater initial stand percentages at Dickinson than the other entries and maintained greater survival percentages for the duration of the study. Sunburst and Trailblazer ranked first or second in biomass yield in all years at Dickinson (Table 4) although biomass yield of Dacotah was not significantly lower in the third production year, 2003. Summer, originating from a Nebraska collection of genotypes, had the lowest initial stand establishment at all locations (Fig. 2), possibly due to inherent low seed mass for this cultivar (Johnson, 1983). Survival percentage of Summer, with an average heading date approximately 7 d earlier than Sunburst, did

Table 4. Biomass yields of eight switchgrass cultivars and experimental strains measured at three North Dakota locations for 3 yr and pooled over two harvest dates.

	Mandan Site 1			Mandan Site 2			Dickinson		
	2000	2001	2002	2000	2001	2002	2001	2002	2003
	Mg ha^{-1}								
Dacotah	5.27	8.09	2.49	7.60	9.46	2.20	3.20	5.57	4.50
ND3743	5.34	7.75	2.05	6.45	8.79	2.14	3.26	4.73	3.84
Summer	6.32	9.42	3.05	9.83	8.33	2.66	3.00	3.76	2.94
Sunburst	8.81	10.52	3.28	10.48	12.48	3.20	5.22	7.55	5.25
Trailblazer	8.32	9.27	3.17	10.19	10.94	2.58	5.62	7.59	4.66
Shawnee	7.39	6.72	2.62	10.08	7.97	2.38	4.22	5.74	3.53
OK NU-2	6.03	6.13	2.00	9.37	8.32	2.46	4.49	5.35	3.69
Cave-In-Rock	7.92	4.75	2.18	9.58	5.93	2.40	3.46	4.54	3.42
Mean	6.92	7.83	2.60	9.20	9.03	2.50	4.06	5.61	3.98
$LSD_{0.05}$	0.94	1.61	0.48	1.41	1.16	0.41	0.59	1.02	0.88

Table 5. Biomass yields of switchgrass averaged over eight cultivars and experimental strains at mid-August and mid-September harvest dates at three North Dakota locations for 3 yr.

	Mandan Site 1		Mandan Site 2		Dickinson	
Year	Aug.	Sept.	Aug.	Sept.	Aug.	Sept.
	Mg ha^{-1}					
2000	6.90a†	6.95a	9.34a	9.06a	–	–
2001	7.49b	8.18a	8.23b	9.82a	4.14a	3.97a
2002	2.56a	2.65a	2.49a	2.52a	5.70a	5.51a
2003	–	–	–	–	2.77b	5.19a

† Mean biomass yield comparisons between harvest dates within each year and location are significantly different ($P \leq 0.05$) if followed by a different letter.

not decline as sharply over time as the southern-most populations Shawnee, OK NU-2, and Cave-In-Rock. Stand percentage of Summer was lower than the other entries, and Summer ranked last in biomass yield each year although not less than Dacotah, ND3743, and Cave-In-Rock in 2001 and 2002 or less than Shawnee, OK NU-2, and Cave-In-Rock in 2003. Compensatory tillering of plants with relatively low initial stand density resulted in greater stand density (Fig. 3) and biomass yield (Table 4) in 2002 than 2001 at Dickinson. Entries of southern origin all had greater stand density and biomass yields in 2002 than 2001 at Dickinson, unlike the two Mandan sites where survival percentages and biomass yield of these entries decreased in each successive production year.

Growing season precipitation at Mandan in 2002 was approximately 50% of the long-term average, with below-average precipitation for all months except August (Table 1). Soil water content at the two Mandan sites averaged lower for the 2002 growing season than the other years and was extremely limiting at approximately 230 mm of soil water to a 1.2-m soil depth after 15 August (Fig. 1). Biomass yields averaged over entries and harvest dates in 2002 were 33% of 2001 yields at Mandan Site 1 and 28% of 2001 yields at Mandan Site 2 (Table 4). Sunburst, Trailmaster, and Summer had the greatest biomass at Mandan Site 1 in 2002, and Sunburst produced greater biomass than any other entry at Mandan Site 2 in 2002. Biomass yields of the two early maturing entries from North Dakota, Dacotah and ND3743, were low compared with Sunburst in the 2002 drought year at Mandan. Soil water has been reported as a major determinant of biomass yield in switchgrass, with irrigated yields averaging threefold greater than nonirrigated at a site in Texas (Koshi et al., 1982).

No consistent yield pattern existed for mid-August and mid-September harvests at different locations and years. The mid-September harvest had greater biomass yield than mid-August at the two Mandan sites in 2001, a year with abnormally high June and July rainfall (Tables 1 and 5). Dickinson in 2003, a drought year, was the other instance where the mid-September harvest had greater biomass yield than the mid-August harvest. Substantial rainfall occurred at Dickinson after the mid-August harvest, which initiated growth and development of plants that appeared to be in drought-induced dormancy. Average biomass yield increased 87% from the mid-August to the mid-September harvest date in 2003 at Dickinson (Table 5). This rapid accumulation of late-season biomass in response to soil water would not be found in most other grass species that are adapted to the northern Great Plains.

CONCLUSIONS

The three field sites in this study were approximately 450 km north of the area where germplasm for the cultivar Sunburst was collected (Boe and Ross, 1998). Sunburst ranked at or near the top for both survival and biomass yield in all environments when compared with other entries in this study. These results support the conclusion of Vogel et al. (1985) that moving switchgrass populations north of their area of origin would result in greater biomass yield. The observation of Moser and Vogel (1995) that warm-season grass species should not be moved more than 500 km north of their area of origin because of potential winter injury is also supported by the results of this study. The five entries whose origin was greater than 500 km south of the study sites were all subject to winter injury and loss of stand.

Biomass yield was closely associated with availability of soil water. Western North Dakota is subject to periodic drought and wide fluctuations in precipitation that would jeopardize the capability of producers to provide a consistent supply of switchgrass biomass for biofuel purposes.

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